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***Abstract*—In this research, transportation mode and load route selection problems are integrated with the hub location problem in a single mathematical formulation to find the optimal design of intermodal transportation networks. Economies of scale are modeled utilizing a stepwise function that relates the per container transportation cost to the amount of flow between two nodes. A heuristic method combining a genetic algorithm and the shortest path algorithm was developed to solve this integrated planning problem. Computational experiments were completed to evaluate the performance of the proposed heuristic for different problem instances. At the end, conclusions are presented and future research directions are discussed.**

Keywords— intermodal transportation, hub network design, integrated planning, integer programming, genetic algorithm, heuristic

I. Introduction

Intermodal freight transportation is a valid alternative to long-haul over the road transportation that can reduce costs, congestion, and the negative environmental effects that are usually observed with the most predominant transportation mode. Intermodal freight transportation is defined as using at least two different transportation modes to move freight that is in the same transportation unit (e.g., a shipping container) from origin to destination without actually handling the goods when changing transportation modes [1].

One key strategic planning decision in intermodal freight transportation is the design of its logistics network. Different network topologies including point to point, corridor, hub and spoke, connected hubs, static routes and dynamic routes have been used to handle intermodal transportation service [2]. In this research, a hybrid network topology that combines connected hubs with point to point is considered for intermodal transportation. Therefore, loads can be shipped directly from their origin to destination or they can be moved from their origins to a hub or terminal. At the hub, all needed transfers are handled and loads are consolidated to be transported to another hub or to their destinations. In this configuration, the larger flows between hubs reduce total transportation costs due to economies of scale resulting from the consolidation of loads. By considering this hybrid network topology, this research is not addressing the traditional hub-and-spoke network design problem anymore.

Several strategic, tactical and operational decisions and constraints need to be considered when designing an intermodal network. For example, hub locations are determined in the strategic phase and affect the selection of resource levels at terminals and transportation modes to be used which are established at the tactical level. Similarly, the previous decisions affect the selection of specific routes for loads which are determined during the operational phase. These decisions are not independent and should be handled together to optimize the intermodal transportation system performance. However, in most previous research studies, these decisions have been made separately in a multi-stage approach in which decisions made at one level are used as input for the next level. In this research, hub locations, transportation mode selection, and load routing for each load are all considered in a single integrated mathematical model to find the optimal design for an intermodal network.

In practice, the per container transportation cost depends on the degree of consolidation at terminals due to economies of scale (i.e., transportation cost per container will decrease more as more containers are consolidated at terminals). However, most previous research considers a constant discount factor for all inter-hub transportation movements regardless of the amount of containers that is shipped between two nodes [3]. While we are able to obtain valuable insights by using a constant discount factor, there is a need for a more accurate cost function to make the mathematical formulation more applicable in real world instances. The mathematical model presented in this research considers a stepwise cost function that determines the per container transportation cost as a function of the amount of containers that are shipped between node pairs. Using this stepwise cost function, we can model real world cost functions accurately. However, considering this stepwise cost function makes the Integrated Intermodal Logistics Network Design (IILND) problem significantly harder to solve. This is because with this stepwise cost function, the transportation mode and route selection problems become NP-hard problems regardless of the hub locations [4]. In order to solve the IILND problem, a heuristic method combining a genetic algorithm (GA) and the shortest path algorithm (SPA) was developed.

A particular contribution of this research is that the transportation mode of each shipment leg can be explicitly determined with this new mathematical model in comparison to previous models that only determine the inter-hub shipment transportation mode and assume that all other shipments are handled by truck. Also, previous research studies restrict the number of hubs that each load can visit in its movement from origin to destination (i.e., usually to two hubs). This assumption may be valid in small logistics networks, however in larger networks especially for long-haul or international transportation, a load may pass through several hubs in order to be consolidated with other loads or be transferred to a different transportation mode to reduce transportation costs. As such, this assumption is relaxed in the current study and loads are allowed to visit as many hubs as needed between origin and destination to reduce the total network cost.

II. Literature Review

As the market for intermodal freight transportation grows within the transportation industry, a growing number of research studies have been completed in this area. Reference [5] classified these studies according to two criteria: 'type of operator' and 'time horizon of the operations problem.' Several research studies have been completed in each of these categories. More closely related to the current research, [6], [7], [8], [9], [10], [11], [12], [13], and [14] have recently developed models and solution approaches for network operator planning problems. Intermodal logistics network design is one of the most important strategic planning problems that affect the performance of the intermodal transportation system. In this area, hub-and-spoke networks have been studied the most as they are the fundamental network configuration for intermodal freight transportation. Several studies related to the design of hub networks can be found in the literature in many applications related to transportation and telecommunications. References [3], [15] and [16] provide recent comprehensive reviews of various research studies in this area. However, as a particular application area, intermodal freight transportation has its own characteristics and constraints that should be explicitly considered when designing a logistics network using a hybrid hub-based configuration. In particular, most of the hub location literature assumes that no direct shipment between spokes is allowed and that the flow of cargo is limited to visit at most two hubs. These are not realistic assumptions in practice in the context of intermodal freight transportation. Also, most existing work in this area only considers the hub location or hub network design aspect of this problem and ignores the integration of the hub location-allocation decisions with tactical decisions such as transportation mode selection and resource allocation.

Operations research techniques have been consistently used for designing intermodal logistics networks. However, given the complexity and scale of this planning problem, many researchers have mostly relied on heuristic and metaheuristic approaches to obtain near optimal solutions for large problem instances. Mathematical models for intermodal hub network design applications were initially presented by [17], [18] and [19]. Reference [20] proposed an approach for the design and operation of integrated intermodal transportation networks for express package delivery. Reference [21] developed a mixed integer programming model to find the optimal number and location of inland ports for an intermodal transportation network that minimizes total transportation and facility costs. Reference [22] developed an iterative procedure to estimate the potential locations for terminals assuming that each node can be allocated to only one hub in the network. Then, the authors used a mixed integer programming model to determine the optimal locations among those potential locations.

Later, [6] considered the assumptions that each load has service time requirements and can be shipped through at most two hubs. Still, transportation times between two hubs were multiplied by a constant factor to capture the transitioning time at terminals. In a related study, [7] modeled the hub operations as a G/G/1 queuing system to estimate the transitioning time at terminals more accurately. In both of these last two research studies, a tabu search metaheuristic was implemented to find near optimal location-allocations of hubs that minimize the total transportation and fixed hub facilities costs.

Reference [8] developed a couple of two-stage metaheuristic methods for the mixed integer programming model first developed by [18] which allows direct transportation between nodes as well as visiting at most two hubs. The objective of this model was to determine the location-allocation of hubs such that the total transportation cost is minimized. Reference [12] improved the mathematical model of [8] by reducing constraints and variables in the formulation without any extra assumptions. The authors then developed two heuristics to find near optimal hub locations. Reference [9] modified the model of [8] to a bi-objective mixed integer programming model. The authors developed a problem-specific greedy randomized adaptive search procedure (GRASP) to approximate the optimal Pareto set.

In another study, [23] proposed single allocation hub network design models including delivery due date constraints and allowing multiple transportation modes. They used valid inequalities and a heuristic based on Lagrangian decomposition and variable reduction to solve the proposed formulations. Reference [24] also solved a hierarchical hub median problem where shipment of all cargo is restricted to pre-specified time windows by developing a mixed integer programming formulation that is solved with the help of variable fixing rules and valid inequalities. In their model, they minimize the total transportation costs and installation costs per unit of time.

More recently, [13] developed a mathematical model that integrates the load route and transportation mode selection problems within the hub location problem for the intermodal logistics network design problem. However, a constant discount factor is still considered to account for economies of scale for movements between hubs. The authors developed a decomposition approach to obtain exact solutions for several randomly generated instances.

Finally, while most of the previous studies only consider transportation and fixed facility costs, a few recent studies have included other types of costs in the modeling of intermodal logistics networks. CO_2 emissions have been recently considered in the design of intermodal hub networks by [11], [25], [26], and [27].

The reader is referred to comprehensive reviews of research studies in intermodal transportation planning including strategic network design by [5], [28], and [29]. Like most of the previous studies on strategic network design, the current research attempts to minimize the total transportation and fixed facility costs, however the modelling approach of this research integrates the transportation mode and load route selection problems within the hub location problem and relaxes some restrictive assumptions made in previous studies.

III. Methodology

A. Problem Definition

There are N nodes representing origins and destinations of loads, and potential locations for hubs. Fixed hub installation costs at these nodes are considered. Containers in a load can be shipped between two nodes using one of the available transportation modes that connect the two nodes. Each transportation mode has a corresponding transportation cost per mile and per container. However, this transportation cost depends on the amount of containers that are transported on a particular mode between two nodes. As flow between hub nodes increases and consolidation occurs with modes that are able to handle more than one container in a single trip, the transportation cost per container decreases due to economies of scale resulting from the larger flows. Consequently, the per container transportation cost of moving freight between two hubs is less than the per container cost of transportation between a hub and a non-hub node or between two non-hub nodes. However, the transportation time between origin and destination also increases as more hubs are visited in a trip due to delays at the hubs for coordination and load handling. The IILND problem can be defined as determining the locations for hubs, the selection of transportation modes for each load shipment, and the assignment of routes to load shipments such that total hub installation and transportation costs are minimized subject to constraints.

B. Mathematical Model Formulation

A stepwise function that relates the per container transportation cost to the amount of flow between two nodes was used to model the effect of consolidation and economies of scale on the transportation cost for inter-hub movements (Fig. 1). The number of steps in this cost function can be arbitrarily determined based on a particular transportation mode. As a result, the stepwise function can realistically model the transportation cost between two nodes with relatively high precision. This is a different approach than the one used in [30] and [31].

If we let $i, j, k = 1, 2, \ldots, N$ denote indices for nodes, $t = 1, 2, \ldots, T$ be the index for transportation modes, and $r = 1, 2, \ldots, R$ be the index for steps in the transportation cost per container stepwise function, then S_{ijr}^{t} denotes the lower bound flow value of step r in the transportation cost per container stepwise function between nodes i and j via mode t, and C_{ijr}^{t} is the value of step r in the transportation cost per container stepwise function between nodes i and j via mode t. Additional notation for indices and parameters includes $p, q = 1, 2, \ldots, L$ as indices for load shipments, F_i is the fixed cost of installing a hub at node i, d_p is the demand (i.e., number of containers) for load shipment p, H is the maximum number of hubs to open, M is a very large positive number, and $Origin_p$ denotes the origin node for load p.

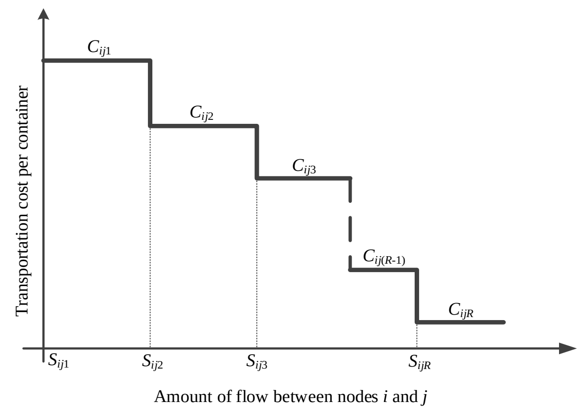

Fig. 1. Stepwise Function for Transportation Cost Per Container

The binary decision variables are Y_i which takes a value of 1 if a hub at node i is open, 0 otherwise; $X_{ij}^{p,t}$ with a value of 1 if load shipment p is moved from node i to node j via mode t, 0 otherwise; and, $Z_{ijr}^{p,t}$ which takes a value of 1 if the number of containers for load shipment p moving from node i to node j via mode t is on the r^{th} step of the transportation cost per container stepwise function, 0 otherwise. The mathematical formulation for IILND follows.

$$\text{Minimize} \sum_i F_i Y_i + \sum_p \sum_t \sum_i \sum_j \sum_r C_{ijr}^{t} d_p Z_{ijr}^{p,t} \qquad (1)$$

Subject to:

$$\sum_t \sum_k X_{ki}^{p,t} - \sum_t \sum_j X_{ij}^{p,t} = \begin{cases} -1 & \text{if } i \text{ is origin of } p \\ 1 & \text{if } i \text{ is destination of } p \\ 0 & \text{otherwise} \end{cases} \qquad \forall p \in L, \forall i \in N \qquad (2)$$

$$\sum_t \sum_j X_{ij}^{p,t} d_p \le M Y_i \qquad \forall p \in L, \forall i \in N - \{Origin_p\} \qquad (3)$$

$$\sum_i Y_i \le H \qquad (4)$$

$$S_{ijr}^{t} - \sum_q X_{ij}^{q,t} d_q < M\left(1 - Z_{ijr}^{p,t}\right) \qquad \forall i, j \in N, \forall r \in R, \forall t \in T, \forall p \in L \qquad (5)$$

$$\sum_q X_{ij}^{q,t} d_q - S_{ijr}^{t} \le M\left(1 - Z_{ij\,(r-1)}^{p,t}\right) \qquad \forall i, j \in N, \forall t \in T, \forall p \in L, r = 2, \ldots, R \qquad (6)$$

$$\sum_r Z_{ijr}^{p,t} = X_{ij}^{p,t} \qquad \forall i, j \in N, \forall t \in T, \forall p \in L \qquad (7)$$

$$Y_i = \{0,1\} \qquad \forall i \in N \qquad (8)$$

$$X_{ij}^{p,t} = \{0,1\} \qquad \forall i, j \in N, \forall t \in T, \forall p \in L \qquad (9)$$

$$Z_{ijr}^{p,t} = \{0,1\} \qquad \forall i, j \in N, \forall r \in R, \forall t \in T, \forall p \in L \qquad (10)$$

Objective function (1) minimizes the total cost consisting of the fixed hub installation cost and the transportation cost for all flows in the network. Constraint (2) enforces flow balance at the nodes in the network. Constraint (3) requires that hubs should be used only if they are selected to be opened. The total number of hubs that can be opened is limited by constraint (4). The transportation cost per container stepwise function is linearized using constraints (5) – (7). And finally, constraints (8) – (10) are the variable type constraints. Note that the value of M could be replaced by the summation of all flows in the network to provide a specific bound for constraints (3), (5) and (6).

C. Solution Approach

As different decisions (i.e., hub location, transportation mode and route selection) are integrated into a single mathematical model, the tractability of the IILND problem presented above is affected by the size of the instances solved. As a result, only small problem instances can be solved to optimality using a commercial solver. To overcome this challenge, a heuristic approach that takes advantage of both Genetic Algorithms (GA) and the Shortest Path Algorithm (SPA) was developed. The method starts by finding the optimal location for a single hub and evaluating the resulting total network cost during the first iteration. The method then moves to the next iteration by increasing the number of hubs to open until opening one more hub increases the total network cost of the solution obtained. During each iteration, the SPA is used to find optimal transportation modes and load routes for all freight loads for a given hub location solution. The resulting total network cost is used to evaluate the fitness of that particular hub location solution. Meanwhile, the GA leads the search for optimal hub locations through the feasible solution space. Therefore, the proposed solution approach starts each iteration with a set of initial hub location solutions, then evaluates them using the SPA, and moves to a new set of hub location solutions by applying GA operations until reaching a stopping criterion.

In the proposed GA, chromosomes represent the allocation of hubs to nodes in the network (i.e., each gene corresponds to the index of a node where a hub is located). Since in the K^{th} iteration of the algorithm, the number of open hubs is equal to K, each chromosome in the population has K genes. For example, if N is equal to 20 and K is equal to 3, a chromosome associated with the solution in which hubs are allocated to nodes 4, 12 and 16 is represented by (*4,12,16*). The initial population for the GA is randomly generated at the beginning of each iteration of the solution approach (i.e., when the number of hubs is increased by one).

To evaluate the hub solutions in each generation of the GA, the total cost for each solution has to be computed. Note that hub locations are fixed for each solution, so the fixed cost of installation is known. However, the transportation cost is not known until the transportation modes and load routes are determined for all loads. The SPA is used to select the transportation modes and load route that minimize the transportation cost for a given load. The SPA can only be applied to networks that have at most one link (i.e., arc) with a fixed cost between two nodes. However, in intermodal transportation networks, there can be multiple arcs between two nodes each representing a different mode of transportation. Also, the transportation costs vary as a function of the amount of containers (i.e., flow) that are shipped on an arc. To overcome these challenges, dummy nodes are defined at locations where multiple transportation modes are available. Each single-mode transportation network is modelled by a set of n dummy nodes and the cost of transitioning loads from a node to its corresponding dummy nodes (i.e., nodes in the same location for different transportation modes) is zero.

At this stage of the proposed solution approach, an iterative procedure is implemented to overcome the non-linear transportation cost between nodes in the network. After the SPA is initially used to determine the transportation modes and load routes for all shipments, the transportation costs per container are recalculated based on the amount of flow between each pair of nodes according to the stepwise transportation cost per container function. Then, the SPA is applied again to the network with the new transportation costs. This iterative process continues until no changes in cost are observed. Note that a constant discount factor could be considered for inter-hub shipments in the initial step to generate solutions that incorporate the consolidation of flow. After all transportation mode and load route selection decisions are final, the total cost is calculated and used as the fitness value of each hub solution in the current GA population.

A combination of elitism and rank selection is used to determine the solutions that are used as input for crossover and mutation operations of the GA. The offspring that result from the application of these GA operations form the population for the next generation of the GA.

The entire process combining the GA with the SPA is repeated until a predetermined number of generations (i.e., the stopping criterion) are produced.

After the GA stops at the end of each iteration, the total cost of the best solution in that iteration is compared to the total cost of the best solution in the previous iteration. If the total cost decreases compared to the previous iteration; the solution method moves to the next iteration by adding one more hub to the number of open hubs and continues to explore an additional reduction in total cost. Otherwise, the solution method stops.

IV. Computational Experiments

Both, randomly generated instances and the Civil Aeronautics Board (CAB) dataset were used to evaluate the performance of the proposed mathematical model and solution approach. The following sub-sections present the experimental design and computational results for both datasets.

A. Experimental Design for Randomly Generated Dataset

Two sets of computational experiments (Set A and Set B) were completed on randomly generated datasets. Set A experiments were used to test the performance of the proposed heuristic when compared to exact solutions obtained for small network instances. Set B experiments were developed to obtain insights about the solutions obtained with the heuristic method for medium size instances. For all computational experiments, random instances of complete networks (i.e., networks where all pairs of nodes are connected to each other by an arc) were generated in which nodes were uniformly distributed in a 1.0 × 0.5 rectangular area. For each problem configuration in Set A, 10 random instances were generated, while five random instances were created for Set B. In all cases, *L* load shipments were randomly generated and their demand (i.e., number of containers) was assigned based on a random value uniformly distributed between 50 and 150 units. In Set A, the size of *L* was set to be equivalent to 5%, 10%, 15%, 20% and 25% of all possible O-D pairs in the complete network. In Set B, the size of *L* was set to be equivalent to 20% of all possible O-D pairs. In addition, limitations were established for the number of transportation modes considered in each problem instance. Half of the generated problem instances had only two transportation modes, while the other half considered three modes.

Regarding cost parameters, the fixed cost of installing a hub at a node (amortized for the length of the planning horizon) was considered to be a random variable that is uniformly distributed between 100 and 150. Also, the transportation cost between nodes *i* and *j* was dependent on the transportation mode selected to connect two nodes. Values for the first step of the transportation cost per container stepwise function were calculated using (11), (12) and (13), according to the number of available transportation modes connecting nodes *i* and *j*. Based on our notation, a higher numbered transportation mode was assumed to provide a less expensive transportation cost per container for long haul shipments, while it was more expensive for short haul transportation. In (11) - (13), *Random*(0,1) refers to a uniformly distributed random variable between 0 and 1. Three steps were considered for the transportation cost per container stepwise function for each transportation mode.

Mode (*t*)	**Maximum transportation cost per container between nodes *i* and *j* (C_{ij1}^{t})**	
1	$\boldsymbol{C_{ij1}^{1}} =$ Distance (i,j) / 2 + *Random*(0,1)	(11)
2	$\boldsymbol{C_{ij1}^{2}} =$ Distance (i,j) / 3 + *Random*(0,1) + 0.05	(12)
3	$\boldsymbol{C_{ij1}^{3}} =$ Distance (i,j) / 4 + *Random*(0,1) + 0.10	(13)

All of the parameters and their respective values used to randomly generate problem instances for both sets A and B are shown in Table I. For the GA used in the proposed solution method, the stopping criterion was set at 50 generations, each containing 40 chromosomes (i.e., hub solutions).

TABLE I. PARAMETERS AND VALUES FOR SETS A AND B

Parameter	***Randomly Generated Dataset***	
	Set A	***Set B***
# of Nodes	10	25, 50
# of Loads	5%, 10%, 15%, 20% and 25% of all possible O-D pairs	20% of all possible O-D pairs
# of Modes	2, 3	2, 3

B. Computational Results for Randomly Generated Datasets

The proposed mathematical model and solution approach for the IILND problem were implemented in MATLAB. All computational experiments were run on a 2.83 GHz Quad Core computer with 8 GB of RAM.

Each instance in Set A was solved using the heuristic solution approach presented above, and the results were compared to optimal solutions obtained using CPLEX 12.2 to assess the performance of the proposed solution approach. The percentage differences between the average optimal solution value obtained with CPLEX and the average heuristic solution value for each problem instance were calculated and are presented in Table II. At the same time, a comparison of the selected hub nodes in both solutions was completed and the average percentage of hubs in the heuristic solution that are present in the optimal solution for each problem instance are also shown in Table II.

As shown in Table II, the heuristic approach consistently obtained solutions that were very close to the optimal solution. Actually, the heuristic approach obtained the optimal solution for all instances with five loads. However, the average percentage cost difference increased with the size of the problem (i.e., as the number of loads increased), but never exceeded 4% with respect to the optimal solution obtained with CPLEX. Also, according to Table II, a relationship between instance size and average percentage of optimal hubs found by the heuristic method was observed. For example, in average 70% of the hubs selected in the optimal solution were found by the heuristic method in instances with 23 loads and two modes. This means that even when the average percentage cost difference was about 3.5%, most of the hubs selected by the heuristic were part of the optimal set. Note that the selection of hubs by the heuristic method was the same as the optimal hub selection obtained with CPLEX in small instances with fewer loads. However, as instance size increased, the percentage of optimal hubs found by the heuristic approach decreased.

TABLE II. HEURISTIC RESULTS FOR SET A INSTANCES AS COMPARED TO OPTIMAL SOLUTIONS

# of Loads	***# of Modes = 2***		***# of Modes = 3***	
	Avg. % Cost Diff.	***Avg. % Opt. Hubs***	***Avg. % Cost Diff.***	***Avg. % Opt. Hubs***
5	0.00	100	0.00	100
9	0.50	100	0.54	100
14	1.00	85	0.60	80
18	3.62	75	1.57	80
23	3.47	70	2.88	50

In terms of computational performance, the average solution times for the heuristic and the exact approaches are reported in Table III. In the instances with fewer loads, the average solution time using CPLEX (i.e. the exact approach) is competitive when compared to the heuristic approach. However, as the size of the instances increased, the average solution time for the exact approach increased very fast while the increase in solution time for the heuristic method was not as significant. In larger instances with 23 loads and three modes, the heuristic approach was able to find a good solutions in less than two minutes, while it took about 2.3 hours to find the optimal solution using CPLEX. Note that in the exact approach, in addition to the solution time, there is a setup time in which the model is setup to be solved by CPLEX. The setup time depends on the number of constraints and decision variables in the mathematical formulation presented above. For networks with 10 nodes, five loads and two transportation modes, there were 6,096 constraints and the average setup time was 14 seconds. While networks with 10 nodes, 23 loads and three transportation modes had 41,838 constraints and an average setup time of 1,476 seconds.

TABLE III. AVERAGE SOLUTION TIMES FOR HEURISTIC AND EXACT APPROACHES FOR SET A INSTANCES

# of Loads	*# of Modes = 2*		*# of Modes = 3*	
	Heuristic (secs)	*Exact (secs)*	*Heuristic (secs)*	*Exact (secs)*
5	10	1	17	2
9	19	7	30	9
14	30	49	44	156
18	41	620	64	1,010
23	67	5,024	87	8,500

While the instances in Set B were not solved to optimality using CPLEX, solutions were obtained by applying the proposed heuristic method. Table IV shows the total network costs and the number of open hubs for the five instances in Set B.

According to Table IV, as the number of transportation modes increases from $T = 2$ to $T = 3$ the total network cost reduces. A reason for this is that the networks with three modes consist of the exact same modes as the networks with two modes plus an additional set of dummy nodes associated with transportation mode 3 which provides less expensive long-haul transportation. In this way, the solution space of the route selection problem grows as the number of modes increases. This results in finding better solutions with lower transportation costs. On the other hand, the number of open hubs decreases when a third transportation mode is considered since a new hub is opened only if the amount of savings that result from the additional consolidation of loads is greater than the fixed cost of opening an additional hub. However, when a third transportation mode that provides less expensive long-haul service is considered, the total transportation cost decreases and there is a reduced chance that opening a new hub would be economically feasible. Also, as the network size increases from 25 to 50 nodes, a greater than or equal number of hubs are required, although the increase is not really significant.

Regarding the computational performance of the proposed heuristic method for these larger problem instances, Fig. 2 shows the average solution times obtained for Set A (i.e., 10 node networks) and Set B (i.e., 25 and 50 node networks) instances with load demand for 20% of all possible O-D pairs. According to Fig. 2, average solution times increased with the size of the instances (i.e., number of nodes and number of transportation modes). The proposed heuristic method was able to obtain solutions in a few minutes for 10 node networks with up to three transportation modes. However, it required more than 53 hours for networks with 50 nodes and three transportation modes. The average solution times for networks with three transportation modes were larger than the solution times for networks with two modes, especially for 50 node networks. Given that the number of dummy nodes and arcs in the network increases with the number of modes in the network, it takes longer for the SPA to find the optimal routes for loads in these instances.

TABLE IV. TOTAL COST AND NUMBER OF OPEN HUBS FOR SET B INSTANCES

Instance	*Measure*	*N = 25, P = 120*		*N = 50, P = 490*	
		T = 2	*T = 3*	*T = 2*	*T = 3*
1	**Cost**	4,503.9	3,991.6	13,277.9	12,973.0
	# of Hubs	4	4	5	5
2	**Cost**	4,792.4	4,390.4	13,987.8	13,023.4
	# of Hubs	5	4	5	4
3	**Cost**	4,900.1	4,394.4	14,230.4	13,430.0
	# of Hubs	5	3	5	5
4	**Cost**	4,797.9	4,136.2	14,180.6	12,696.2
	# of Hubs	5	4	5	5
5	**Cost**	4,862.4	4,367.8	14,183.2	12,755.6
	# of Hubs	5	3	5	5

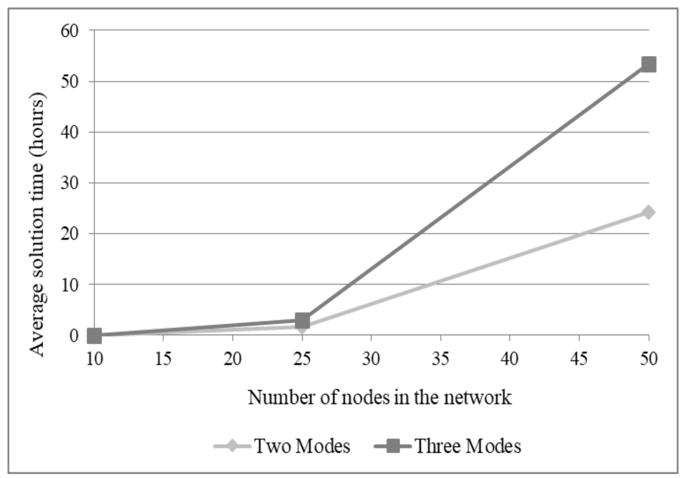

Fig. 2. Heuristic Method Average Solution Times for Set A and Set B Instances (20% of All Possible O-D Pairs)

C. Experimental Design for CAB Dataset

The CAB dataset is one of the most commonly used datasets for testing hub location formulations and solution methods. Even though the CAB dataset is not designed for intermodal transportation networks, it was modified for evaluating the performance of the developed mathematical formulation and solution approach in a realistic instance. The CAB dataset consists of the 25 largest cities in the United States in which all possible origin-destination pairs have a positive demand. In our experimentation, the container transportation cost between nodes i and j was determined based on the transportation mode selected to connect two nodes and the distance between these nodes. Values for the first step of the transportation cost per container stepwise function were calculated using (14)-(16), according to the number of available transportation modes connecting nodes i and j. The CAB dataset was solved considering both two and three transportation modes to evaluate the effect of integrating more transportation modes on the performance of the resulting intermodal logistics networks. Three steps were considered for the transportation cost per container stepwise function for each transportation mode.

Mode (*t*)	**Maximum transportation cost per container between nodes *i* and *j* (C_{ij1}^{t})**	
1	C_{ij1}^{1} = Distance (i,j) / 25,000	(14)
2	C_{ij1}^{2} = Distance (i,j) / 40,000	(15)
3	C_{ij1}^{3} = Distance (i,j) / 50,000	(16)

In addition, regarding the fixed cost of installing a hub at a node, two different scenarios where considered. In Scenario I, all nodes had the same fixed hub installation cost. The CAB dataset was solved considering the fixed costs are 5,000, 10,000, 25,000 and 50,000. In Scenario II, the fixed hub installation cost was not equal for all nodes and was proportional to the total amount of demand flow of each node. In Scenario II, the fixed hub installation cost for node i was calculated using (17).

$$F_i = \text{Total demand flow of node } i\ /\ \theta \tag{17}$$

Where θ represents a proportionality constant. The CAB dataset was solved considering four different values of θ = 10, 20, 50 and 100.

D. *Computational Results for CAB Dataset*

Solutions for the CAB dataset were obtained by applying the proposed heuristic method. Table V shows the total network costs and the number of open hubs for different values of fixed hub installation cost and different number of transportation modes in the network for Scenario I.

When the hub installation cost is large, the amount of savings that results from opening a new hub does not compensate the fixed cost of opening an additional hub. Therefore, according to Table V, the number of open hubs depends on the fixed hub installation cost at each node. Moreover, increasing the fixed installation cost from 5,000 to 50,000 increases the percentage of fixed cost in the total network cost from about 7% to 26% when there are two transportation modes in the network.

Even though integrating more transportation modes can increase planning costs as more stakeholders are involved that may have conflicting interests, it was shown to reduce the transportation cost. Planning costs of integrating more transportation modes into a single intermodal transportation logistics network are not considered in this research and are a potential area for future research.

Similar to Scenario I, in Scenario II, the number of open hubs increases by decreasing the fixed hub installation cost, while the transportation cost decreases by increasing the number of transportation modes integrated in the intermodal network (Table VI).

TABLE V. TOTAL COST AND NUMBER OF OPEN HUBS FOR SCENARIO I

Fixed Cost	***T* = 2**			***T* = 3**		
	Total Cost	***% Fixed Cost***	***# of Hubs***	***Total Cost***	***% Fixed Cost***	***# of Hubs***
5,000	135,344	7.39	2	110,275	9.07	2
10,000	145,344	13.76	2	120,275	16.63	2
25,000	162,949	15.34	1	135,359	18.47	1
50,000	187,949	26.60	1	160,359	31.18	1

TABLE VI. TOTAL COST AND NUMBER OF OPEN HUBS FOR SCENARIO II

θ	***T* = 2**			***T* = 3**		
	Total Cost	***% Fixed Cost***	***# of Hubs***	***Total Cost***	***% Fixed Cost***	***# of Hubs***
10	179,239	25.77	2	152,631	30.27	2
20	126,591	31.67	3	102,074	39.28	3
50	118,301	61.31	5	94,329	68.33	5
100	117,512	27.42	5	93,903	38.12	5

V. CONCLUSIONS AND FUTURE WORK

Designing the intermodal logistics network is one of the critical strategic decisions in intermodal transportation planning. While integrating tactical and operational decisions such as transportation mode and load route selection, and explicitly considering more realistic assumptions when modelling this problem increase the potential applicability of the resulting logistics network design, the complexity of the integrated mathematical model is significantly affected. Consequently, obtaining high quality solutions in reasonable times is very valuable in this context. In this research, a heuristic approach combining a genetic algorithm and the shortest path algorithm was developed to solve this integrated planning problem.

According to the experimental results, solutions obtained with the proposed heuristic approach are very close to the optimal solution for small problem instances with 10 nodes. However, the percentage cost difference between optimal and heuristic solutions increases with the size of the problem. More importantly, the average percentage of optimal hubs found by the heuristic solution approach is large even as instance sizes grow. In fact, the heuristic solution approach was able to obtain all optimal hubs for several small instances. In these cases, the difference between the total cost obtained using the heuristic method and the optimal solution was due to the selection of non-optimal routes and transportation modes by the heuristic method. Also, the proposed heuristic approach is able to solve instances with 25 nodes from the CAB dataset. The results indicate that when the hub installation cost is large, the amount of savings that results from opening a new hub does not compensate the fixed cost of opening an additional hub. Therefore, the number of open hubs depends on the fixed hub installation cost at each node. On the other hand, considering additional transportation modes reduces the total transportation cost.

However, as observed in the computational experimentation, as more transportation modes are considered, the size of the IILND problem increases and the solution approach requires more time to find solutions. Consequently, improving the transportation mode and load route selection portion of the heuristic approach is a potential area for future research.

Also, additional criteria such as transportation time can be incorporated into the mathematical model formulation. For example, in real world problems, each load has a time window constraint that is imposed to satisfy service level requirements. Each shipment would take a different amount of time to move between a given node pair depending on the mode of transportation that is selected. Load consolidation at terminals also takes some time depending on the resource levels at terminals and coordination capabilities of the network operators. Including congestion at terminals would be an interesting extension to the proposed formulation.

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